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DRAWINGS ATTACHED

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- (72) Inventors CARL LESLIE DAMMANN and
FREDERICK ALAN SAAL



(54) IMPROVEMENTS IN OR RELATING TO RECTIFIER CIRCUITS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195, Broadway, New York City, New York State, United States of America, a Corporation organised and existing under the laws of the State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to rectifier circuits and, more particularly, to so-called precision rectifiers with dual diode-resistor feedback paths.

Precision rectifiers, as opposed to power rectifiers, aim to produce an accurate rectified version of the input signal and are used in signal processing systems. They are particularly useful in the coder stages of PCM systems. A typical rectifier circuit is disclosed in the *Handbook of Operational Amplifiers Applications*, by the Applications Engineering Section of Burr-Brown Research Corporation (1963), on page 73. This rectifier circuit produces an accurate rectified version of the input voltage except when the input is readily switched to zero. When this happens, the diode-resistor feedback paths open, causing the gain of the operational amplifier to increase which, in turn, causes a corresponding reduction in the amplifier's bandwidth. This reduction in bandwidth causes poor transient response and, therefore, reduces the accuracy of rectification. Previous attempts to overcome this problem involved forward biasing the feedback diodes to limit their maximum feedback resistance. Although this kept the gain of the amplifier from increasing to a point where the time constant was adversely affected it produced a rounding of the rectifier characteristic and corresponding inaccuracies in the rectification.

The present invention seeks to provide

rectifier circuits having improved accuracy and bandwidth over the input voltage range, including those input signals near zero.

According to this invention a rectifier circuit includes an operational amplifier having an input connected through a first input resistance to the input of said circuit, a first feedback diode having its anode connected to an output of said amplifier and to the cathode of a second feedback diode, first and second feedback resistances connected respectively between the cathode of said first diode and said amplifier input, and between the anode of said second diode and said amplifier input, a first output resistance connected between the output of said circuit and the junction between one of said diodes and that one of said feedback resistances connected thereto, a second output resistance connected between the input and output of said circuit, a third feedback resistance connected between the input and output of said amplifier for reducing the gain thereof when said first and second diodes are non-conductive, and means connected between said amplifier output and said circuit output for providing a high resistance when the signal at said circuit input is of one polarity and a lower resistance when said signal is of the opposite polarity, thereby to compensate for error in the circuit output due to said third feedback resistance.

In one embodiment of the invention said means comprises a further operational amplifier having a second input resistance connected between an input thereto and said amplifier output, a third feedback diode having its anode connected to an output of said further amplifier and to the cathode of a fourth feedback diode, fourth and fifth feedback resistances connected respectively between the cathode of said third diode and said further amplifier input, and between the anode of said fourth diode and said further amplifier input, a third output resistance

connected between said circuit output and the junction between one of said third and fourth diodes and that one of said feedback resistances connected thereto, and a fourth output resistance connected between said amplifier output and said circuit output. The first output resistance may be connected between said circuit output and the cathode of said first diode, and said third output resistance connected between said circuit output and the cathode of said third diode.

The invention will now be described by way of example with reference to the accompanying drawings, in which:—

FIG. 1 is a schematic circuit diagram of a known rectifier;

FIGS. 2A, 2B, 2C and 2D show the operation of the rectifier of FIG. 1;

FIGS. 3A and 3B show the loss of frequency response with the rectifier of FIG. 1;

FIGS. 4A, 4B and 4C show the effect of providing an additional feedback resistor in a known rectifier;

FIG. 5 is a schematic circuit diagram of an exemplary embodiment of the invention;

FIG. 6 is a schematic circuit diagram showing the embodiment of FIG. 5 but using a known half-wave rectifier to replace the switch and resistor of FIG. 5; and

FIGS. 7A, 7B and 7C show the operation of the circuit of FIG. 6.

Referring now to FIG. 1, in a known rectifier a circuit input terminal 15 is connected to a terminal 11 and a resistance 21 (R_{21}) is connected between terminal 11 and a terminal 12. The input of an operational amplifier 20 is also connected to terminal 12. The output of operational amplifier 20 is connected to a terminal 28 as are the anode of a diode 24 and the cathode of a diode 25. The cathode of diode 24 is connected to a terminal 29. A resistance 22 (R_{22}) is connected between terminals 12 and 29. The anode of diode 25 is connected through a resistance 23 (R_{23}) to terminal 12. A resistance 26 (R_{26}) is connected between terminal 29 and circuit output terminal 13. A resistance 10 (R_{10}) is connected between terminal 11 and output terminal 13. In this circuit resistances 10, 21 and 26 are equal, resistance 22 is equal to 23, and resistance 10 is one-half resistance 22. The rectifier as shown in FIG. 1 is used as a coder stage in a PCM system and, therefore, output terminal 13 is connected to the summing junction of the operational amplifier of the next stage.

The current I_1 , which passes through resistance 10, is shown in FIG. 2A. The current I_2 , which passes through resistance 26, is shown in FIG. 2B. When the input voltage is positive, the voltage E_D at terminal 28 is negative and diode 24 will not conduct. Therefore, the current I_2 is zero whenever the input voltage is positive. When the input

voltage is negative, the voltage at terminal 29 is positive and follows the input voltage with a gain of minus two, as shown in FIG. 2B. These two currents, I_1 and I_2 , combine to produce the output current shown in FIG. 2C. The curve of FIG. 2D shows what happens at the output of the operational amplifier in the region where the input voltage is nearly zero. As shown in FIG. 2D, the gain of the operational amplifier is very high when neither diode 24 nor diode 25 is conducting. After they begin to conduct the output of the operational amplifier follows the input voltage with a gain of minus two.

FIG. 3A shows the effect of this change in gain on the bandwidth of the operational amplifier. When the diodes are conducting, the circuit operates with a closed loop gain, A_{cl} , of 6 db. This allows the operational amplifier to have a time constant T_{cl} . As the feedback loops open, the gain approaches its open loop value, A_{ol} , and the time constant of the amplifier approaches its open loop value, T_{ol} . The effect of this on the rectification can be seen from FIG. 3B. As the output voltage of the amplifier approaches zero the time constant changes from T_{cl} to T_{ol} . This causes a trailing edge which represents an inaccuracy in the rectification. This inaccuracy causes problems when the circuit is used as a coder stage in PCM systems.

To overcome or reduce this loss of bandwidth a feedback resistor R_{27} is connected (in FIG. 5) between terminals 12 and 28. This causes the gain of the operational amplifier, when the diode-resistor feedback paths are open, to be held to a lower value than that shown in FIG. 3A. The effect of adding this resistor is shown by comparing FIG. 4A with FIG. 2D. The gain in the region where the input signal is near zero has been significantly reduced. This causes the current I_2 to appear as shown in FIG. 4B. The rounding of the curve is caused by the diode characteristic. The translation to the left is caused by the reduced gain in the region near zero and the current diverted from the output through the feedback resistance. When the current I_1 and I_2 are summed at the output the curve of FIG. 4C is produced. As can be seen from this curve, there is a significant error in the output current of the rectifier. This could be partially corrected by biasing the circuit to the point V_{10} , but this point is dependent on the diode characteristic and would, therefore, change with temperature.

The reduction or elimination of this error in the output current will now be described with reference to FIG. 5 in which those parts having the same function as in FIG. 1 have the same references. As previously mentioned, resistance 27 reduces the gain of the circuit during the time when the diode-resistance feedback paths are open. A means

for cancelling the error in the output current is provided by resistance 31 (R_{31}) and a switch 40 connected in series between terminal 28 and the output terminal 13. The switch 40 is made to close when the voltage at terminal 28 is greater than zero and open when it is less than zero. In this circuit

$$R_{10}=R_{21}=R_{24}; \quad R_{22}=R_{23};$$

$$R_{22}=2R_{10}; \quad R_{27}=2R_{31};$$

10 and

$$R_{27} \gg R_{22}.$$

This arrangement provides precision rectification without loss of bandwidth and with compensation for the error in the output current produced by resistance 27. The correction can be illustrated by assuming that the current through resistance 21 for an input, $-E_{in}$, is I and the current diverted through feedback resistance 27 is ΔI . Since the currents entering and leaving the summing junction at terminal 12 must be equal, the current through resistance 22 is $I - \Delta I$. Therefore, the current gain of two for the circuit, which is determined by resistance 26 and resistance 22, causes the current to the output through resistance 26 to be $2(I - \Delta I)$. The error current, $2\Delta I$, is then restored to the output by supplying current through a resistor (R_{31}) with half the value of the feedback resistance 27.

The switch 40 in resistance 31 may comprise another rectifier. FIG. 6 shows such an arrangement.

In FIG. 6 those elements which have the same function as in FIGS. 1 and 5 have the same references. Resistance 37 (R_{37}) is connected between terminal 28 and the circuit output terminal 13. Also, resistance 31 is connected in series with a unity gain half-wave rectifier between terminals 28 and 13. The unity gain half-wave rectifier comprises a resistance 36 (R_{36}) connected between terminal 28 and the input of an operational amplifier 30 the output of which is connected to the anode of a diode 34 and the cathode of a diode 35. The cathode of diode 34 is connected through a resistance 32 (R_{32}) to the input of amplifier 30 and through resistance 31 (R_{31}) to the circuit output terminal 13. The anode of diode 35 is connected through a resistance 33 (R_{33}) to the input of amplifier 30. In this arrangement $R_{32}=R_{33}=R_{36}$, and $R_{31}=R_{37}=1/2R_{27}$.

FIG. 7 illustrates the operation of FIG. 6. The current I_3' through resistance 37 is shown in FIG. 7A. The current I_3'' through resistance 31 is shown in FIG. 7B. FIG. 7B shows that when the voltage at terminal 28 is positive, diode 34 opens and there is no current I_3'' . However, when the voltage at

terminal 28 is negative, the current I_3' is related to it by resistance 31. When the currents I_3' and I_3'' are combined, the current I_3 of FIG. 7C is produced. This is identical to having switch 40 of FIG. 5 open when the voltage at terminal 28 is less than zero and closed when it is greater than zero. The unity gain half-wave rectifier of FIG. 6 will suffer from the transient response problem mentioned previously but, as this will cause an error only in the correction current and not in the principal rectifier signal, its effect for most purposes can be ignored.

WHAT WE CLAIM IS:—

1. A rectifier circuit including an operational amplifier having an input connected through a first input resistance to the input of said circuit, a first feedback diode having its anode connected to an output of said amplifier and to the cathode of a second feedback diode, first and second feedback resistances connected respectively between the cathode of said first diode and said amplifier input, and between the anode of said second diode and said amplifier input, a first output resistance connected between the output of said circuit and the junction between one of said diodes and that one of said feedback resistances connected thereto, a second output resistance connected between the input and output of said circuit, a third feedback resistance connected between the input and output of said amplifier for reducing the gain thereof when said first and second diodes are non-conductive, and means connected between said amplifier output and said circuit output for providing a high resistance when the signal at said circuit input is of one polarity and a lower resistance when said signal is of the opposite polarity, thereby to compensate for error in the circuit output due to said third feedback resistance.

2. A circuit as claimed in claim 1 wherein said means comprises a further operational amplifier having a second input resistance connected between an input thereto and said amplifier output, a third feedback diode having its anode connected to an output of said further amplifier and to the cathode of a fourth feedback diode, fourth and fifth feedback resistances connected respectively between the cathode of said third diode and said further amplifier input, and between the anode of said fourth diode and said further amplifier input, a third output resistance connected between said circuit output and the junction between one of said third and fourth diodes and that one of said feedback resistances connected thereto, and a fourth output resistance connected between said amplifier output and said circuit output.

3. A circuit as claimed in claim 2 where-



for cancelling the error in the output current is provided by resistance 31 (R_{31}) and a switch 40 connected in series between terminal 28 and the output terminal 13. The switch 40 is made to close when the voltage at terminal 28 is greater than zero and open when it is less than zero. In this circuit

$$R_{10}=R_{21}=R_{26}; \quad R_{22}=R_{23};$$

$$R_{22}=2R_{10}; \quad R_{27}=2R_{31};$$

10 and

$$R_{27} \gg R_{22}.$$

This arrangement provides precision rectification without loss of bandwidth and with compensation for the error in the output current produced by resistance 27. The correction can be illustrated by assuming that the current through resistance 21 for an input, $-E_{in}$, is I and the current diverted through feedback resistance 27 is ΔI . Since the currents entering and leaving the summing junction at terminal 12 must be equal, the current through resistance 22 is $I - \Delta I$. Therefore, the current gain of two for the circuit, which is determined by resistance 26 and resistance 22, causes the current to the output through resistance 26 to be $2(I - \Delta I)$. The error current, $2\Delta I$, is then restored to the output by supplying current through a resistor (R_{31}) with half the value of the feedback resistance 27.

The switch 40 in resistance 31 may comprise another rectifier. FIG. 6 shows such an arrangement.

In FIG. 6 those elements which have the same function as in FIGS. 1 and 5 have the same references. Resistance 37 (R_{37}) is connected between terminal 28 and the circuit output terminal 13. Also, resistance 31 is connected in series with a unity gain half-wave rectifier between terminals 28 and 13. The unity gain half-wave rectifier comprises a resistance 36 (R_{36}) connected between terminal 28 and the input of an operational amplifier 30 the output of which is connected to the anode of a diode 34 and the cathode of a diode 35. The cathode of diode 34 is connected through a resistance 32 (R_{32}) to the input of amplifier 30 and through resistance 31 (R_{31}) to the circuit output terminal 13. The anode of diode 35 is connected through a resistance 33 (R_{33}) to the input of amplifier 30. In this arrangement $R_{22}=R_{33}=R_{36}$, and $R_{31}=R_{37}=1/2R_{27}$.

FIG. 7 illustrates the operation of FIG. 6. The current I_3' through resistance 37 is shown in FIG. 7A. The current I_3'' through resistance 31 is shown in FIG. 7B. FIG. 7B shows that when the voltage at terminal 28 is positive, diode 34 opens and there is no current I_3'' . However, when the voltage at

terminal 28 is negative, the current I_3' is related to it by resistance 31. When the currents I_3' and I_3'' are combined, the current I_3 of FIG. 7C is produced. This is identical to having switch 40 of FIG. 5 open when the voltage at terminal 28 is less than zero and closed when it is greater than zero. The unity gain half-wave rectifier of FIG. 6 will suffer from the transient response problem mentioned previously but, as this will cause an error only in the correction current and not in the principal rectifier signal, its effect for most purposes can be ignored.

WHAT WE CLAIM IS:—

1. A rectifier circuit including an operational amplifier having an input connected through a first input resistance to the input of said circuit, a first feedback diode having its anode connected to an output of said amplifier and to the cathode of a second feedback diode, first and second feedback resistances connected respectively between the cathode of said first diode and said amplifier input, and between the anode of said second diode and said amplifier input, a first output resistance connected between the output of said circuit and the junction between one of said diodes and that one of said feedback resistances connected thereto, a second output resistance connected between the input and output of said circuit, a third feedback resistance connected between the input and output of said amplifier for reducing the gain thereof when said first and second diodes are non-conductive, and means connected between said amplifier output and said circuit output for providing a high resistance when the signal at said circuit input is of one polarity and a lower resistance when said signal is of the opposite polarity, thereby to compensate for error in the circuit output due to said third feedback resistance.

2. A circuit as claimed in claim 1 wherein said means comprises a further operational amplifier having a second input resistance connected between an input thereto and said amplifier output, a third feedback diode having its anode connected to an output of said further amplifier and to the cathode of a fourth feedback diode, fourth and fifth feedback resistances connected respectively between the cathode of said third diode and said further amplifier input, and between the anode of said fourth diode and said further amplifier input, a third output resistance connected between said circuit output and the junction between one of said third and fourth diodes and that one of said feedback resistances connected thereto, and a fourth output resistance connected between said amplifier output and said circuit output.

3. A circuit as claimed in claim 2 where-



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- in said first output resistance is connected between said circuit output and the cathode of said first diode, and said third output resistance is connected between said circuit
- 5 output and the cathode of said third diode.
4. A circuit as claimed in claim 3 wherein said third feedback resistance is substantially larger in value than said first feedback resistance.
- 10 5. A circuit as claimed in claim 3 or 4 wherein said first input resistance, said first output resistance, and said second output resistance are substantially equal in value.
- 15 6. A circuit as claimed in claim 3, 4 or 5 wherein said first and second feedback resistances are substantially equal in value and substantially equal to twice the value of said first input resistance.
7. A circuit as claimed in any one of claims 3 to 6 wherein said second input resistance, and said fourth and fifth feedback resistances are substantially equal in value.
- 20 8. A circuit as claimed in any one of claims 3 to 7 wherein said third and fourth output resistances are substantially equal in value and equal to one-half the value of said third feedback resistance.
- 25 9. Rectifier circuits substantially as herein described with reference to FIGS. 5 to 7 of the accompanying drawing.
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- C. S. T. BUCKLEY,
Chartered Patent Agent,
5, Mornington Road,
Woodford Green, Essex.
Agent for the Applicants.

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